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Flame-balls aare stationary spherical premixed flames observed in certain near-limit mixtures. Sufficiently large flame-balls are subject to a three-dimensional instability which defines a maximum mixture strength for which steady flame-balls can exist. The researchers studied the dynamics of flame-balls in the neighborhood of the neutral stability point and show that there is a transcritical bifurcation and the dynamics is governed by a fifth-order system of nonlinear ordinary differential equations. The late time behavior of the solution of these equations corresponds either to a stationary sphere (stable solution) or a growing prolate spheroid. Prolate spheroids are observed experimentally, and the relationship between the experimental observations and the theoretical predictions.

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FINAL REPORT ON AFOSR 90-0220, 90/5/1 - 93/4/30

PRINCIPLE INVESTIGATOR: J.BUCKMASTER

Research

We describe here the research done during the contract period.

ACOUSTICS

Acoustic instabilities are of great importance in rocket motor applications. We have shown that flames containing dispersed particles can be subject to an instability driven by the slip between the two phases. A paper was presented at the 24th International Symposium on Combustion, and published in the Proceedings. The abstract is:

An Acoustic - Instability Theory for Particle - Cloud Flames

J. Buckmaster, U. of Illinois, Urbana, IL 61801

P. Clavin, Universite de Provence

A theory is described for the response to acoustic disturbances of a premixed particle-cloud/air flame traveling in a tube. When, in turn, these disturbances are generated by the vibration of the flame, acoustic instabilities are generated, driven by the thermal and kinematic slip between the gas and solid phases. A simple numerical strategy is described, applicable to any flame structure, and this is applied to a simple model. For some parameter values instability is predicted for all modes, including the fundamental (1/4 - wave). Berlad et al. have carried out experiments in which they report a 1/4 - wave instability, and the relevance of the theory to these observations is discussed.

A sequel to this is the following paper that has been completed and submitted for publication. It will be presented at the 14th International Conference on Explosions and Reactive Systems.

Intrinsic and acoustic instabilities in flames fueled by multiphase mixtures. C.J.Lee, J.Buckmaster, and M.DiCicco.

This is a continuation of '*An acoustic instability theory for particle cloud flames*' J.Buckmaster & P.Clavin, presented at the 24th Symposium on Combustion We have examined the behavior of the flame after it leaves the neighborhood of the ignition point at the open end of the tube. We have uncovered an interaction between the acoustic mode and an intrinsic instability mode (i.e. a natural instability of the flame that is unconnected to the acoustics) which can lead to curious phenomena. Thus 'mode-crossing' can occur. An oscillation corresponding to the fundamental can be seen initially, but as the flame proceeds down the tube this transitions smoothly to the first harmonic. Also the first harmonic is converted to the fundamental.

The paper also includes a discussion of acoustic instabilities in spherical flames. The significance here is that experiments are often done in spherical configurations in order to avoid acoustic instabilities, but the condensed phase driven phenomenon persists in this geometry.

The paper also includes a discussion of mixture nonuniformities generated by acoustic waves in a stream of evaporating droplets. This, we believe, could be important in certain instabilities observed in gas turbines running at low speeds.

This latter aspect has been expanded upon in the thesis of M.DiCicco and a paper on this work will be presented at the AIAA Aerospace Sciences Meeting, Reno, Jan. '94.

NEAR-LIMIT FLAME BEHAVIOR

We have carried out a number of investigations into flame behavior close to the flammability limit which we believe has shed substantial light onto this important area. Some of this work is specifically relevant to lean hydrogen mixtures. There is evidence that knowledge of hydrogen kinetics at modest flame temperatures is not accurate. We believe that our studies will play an important role in correcting this deficiency. Hydrogen kinetics is of importance in such applications as the National Aerospace Plane, and uncertainties in the low temperature regime may have implications insofar as ignition and holding predictions are concerned.

The following paper has been published in the journal Combustion Science and Technology. Its abstract follows:

A Flame-String Model and its Stability

J.Buckmaster

Barely flammable mixtures with small Lewis numbers can support "flame-balls", stationary spherical, premixed flames for which the mass-averaged velocity is zero everywhere. The theory of flame-balls is on a sound footing. Recent experiments by Whaling and Ronney show that, for certain mixtures, g-jitter can stretch a flame-ball into a long cylinder of flame, a "flame-string". Flame-strings display a peristaltic instability and break up into discrete flame balls, in appearance similar to a jet of liquid breaking up into drops under the influence of surface tension. A simple theory of flame-string structure and stability is described.

The following paper has been published in the Proceedings of the 24th International Symposium on Combustion. Its abstract is:

The Three-Dimensional Dynamics of Flame-Balls

J. Buckmaster, R. Gessman, U. of Illinois
P. Ronney, Princeton U.

Flame-balls are stationary spherical premixed flames observed in certain near-limit mixtures. Sufficiently large flame-balls are subject to a three-dimensional instability which defines a maximum mixture strength for which steady flame-balls can exist. We study the dynamics of flame-balls in the neighborhood of the neutral stability point and show that there is a transcritical bifurcation and the dynamics is governed by a fifth-order system of nonlinear ordinary differential equations. The late time behavior of the solution of these equations corresponds either to a stationary sphere (stable solution) or a growing prolate spheroid. Prolate spheroids are observed experimentally, and the relationship between the experimental observations and the theoretical predictions is discussed.

In addition the PhD thesis of CJ Lee has been completed, and some of the work incorporated into a paper that has also been published in the Proceedings of the 24th International Symposium on Combustion. Its abstract is:

<u>The Effects of Confinement and Heat Loss on Outwardly Propagating Spherical Flames</u>

J. Buckmaster and C. J. Lee, U. of Illinois

The evolution after point ignition of spherical flames subject to radiation losses and confinement (pressure rise) effects, is studied using numerical computations of an asymptotically derived model. Physical ingredients that control or characterize the solution include: Lewis numbers less than 1 so that curvature and stretch enhance the burning for flames less than ~ 10 cm in radius; radiative heat losses which diminish the burning intensity and can lead to quenching; a radial inflow generated by radiative cooling of the burned gas; and pressure rise due to confinement that enhances the burning when the flame radius is a significant fraction of the confinement vessel radius. It is shown that the confinement effect can lead to extreme sensitivity to the initial data, a new result. Solution trajectories for different initial conditions in the flame speed / flame-radius plane coalesce shortly after ignition and follow a common path during several centimeters of travel. But then they can split apart with some solutions quenching, some accelerating through the remainder of the unburned gas.

In collaboration with M.Smooke of Yale University we have carried out the first numerical simulations of flame-balls and written a paper which has been published in *Combustion and Flame*. Its abstract is:

Analytical and Numerical Modeling of Flame-Balls in Hydrogen-Air Mixtures.
J.Buckmaster, M.Smooke, & V.Giovangigli.

Flame-balls are stationary spherical premixed flames observed in certain near-limit mixtures. It is believed that radiative losses are an important stabilizing influence. Numerical solutions of flame balls are constructed for hydrogen/air mixtures using an accurate description of the chemical kinetics, diffusive transport, and radiation losses. A lean limit equivalence ratio of .0866 is predicted and a rich limit of 2.828. For any equivalence ratio between the two limits there are two solutions. One is characterized by a small flame, incomplete reactant consumption, and negligible radiation losses. The other by a large flame, complete consumption of one of the reactants, and significant radiation losses. The maximum temperature varies between 1200K and 900K as the two solution branches are traversed. Much of our discussion is a reprise and modification of previously published analytical results, for these provide physical insight into the nature of the solutions, and suggest that a portion of the large flame branch near the lean limit is stable and so corresponds to observable flames.

In a paper:

Absolute Flammability Limits and Flame-Balls, D.Lozinski, J.Buckmaster, & P.Ronney, submitted for publication in April 1 1993, we have examined the effects of radiation absorption on flame ball structure and incorporated this into a discussion of absolute flammability limits (i.e. limits that are apparatus independent). We believe that our work on flame-balls has illuminated this fundamental issue of combustion science in a unique fashion.

OTHER WORK

An invited review: *The Structure and Stability of Laminar Flames*, J.Buckmaster was written at the beginning of the contract period and has just appeared in Annual Review of Fluid Mechanics, 1993, vol.25, pp. 21-53.

An invited talk 'The Role of Mathematical Modeling in Combustion' was presented at a workshop at ICASE (NASA Langley) in the fall of '92 and will be published in the work shop proceedings. The PI is an editor of these proceedings.

We have completed a preliminary study of metal burning in oxygen atmospheres, an important safety issue in any technology where oxygen must be stored and used at high pressures. Metal burning is also important in solid propellant rocket motor applications. Experiments reveal some curious dynamics, and our fundamental goal is to explain these phenomena (as a test of our combustion model). We have constructed a steady solution and examined its stability. Our model is based on ideas of Steinberg who has done fundamental experiments in this area. These ideas are controversial and so we are in the process of presenting the work to the combustion community in an informal fashion, seeking constructive criticism before submitting it for publication. This work will be presented at the AIAA Aerospace Sciences Meeting in Reno, Jan. 1994.

In collaboration with Tom Jackson of ICASE (NASA-Langley) we have initiated a study of the structure and stability of flames in mixtures containing large amounts of inert dust. The goal of this work is to improve our understanding of the role of radiation in flames. A preliminary study has been completed and a paper will be written during the summer of '93.

Work has been initiated with D.Lozinski (post-doctoral student supported primarily by the Canadian Government) on diffusion-flame instabilities. We are examing an annular flame and seeking symmetry breaking close to the Damkohler number extinction limit.

Publications during the Contract Period acknowledging AFOSR

J.Buckmaster, G.Joulin, & P.Ronney "The structure and stability of nonadiabatic flame balls', Combustion and Flame, vol. 79, 381--392, 1990.
S.Weeratung, J.Buckmaster, & R.E.Johnson. "A flame-bubble analogue and its stability", Combustion and Flame, vo. 79, 100-109, 1990.
J.Buckmaster & C.J.Lee. "Flow refraction by an uncoupled shock and reaction front", AIAA Journal, vol.28, 1310-1312, 1990.
J.Buckmaster. "The structural stability of oblique detonation waves", Combustion Science and Technology, vol.72, 283-296, 1990.
J.Buckmaster & P.Ronney. "The role of radiation in microgravity flame structures and behavior", Proceedings of the Eurotherm Seminar No.17 'Heat transfer in radiating and combusting systems' Cascais, Portugal, 1990, pp.9-13 in the section 'Heat transfer in flames'.
C.J.Lee & J.Buckmaster. "The structure and stability of flame-balls: a nef analysis", SIAM Journal on Applied Mathematics, vol 51, 1315-1326, 1991.
J.Buckmaster & G.Joulin. "Flame-balls stabilized by suspension in fluid with a steady linear ambient velocity distribution", Journal of Fluid Mechanics, vol.227, 407-427, 1991.
J.Buckmaster, G.Joulin, & P.Ronney. "Modeling of microgravity ignition experiments", article in Recent Advances in Combustion Modeling, ed. B.Larrouturou, World Scientific Series in Advances in Mathematics for Applied Sciences, vol.6, 1-18, 1991. Lectures given at the CEA-EDF-INRIA course on combustion held in Roquencourt.
J.Buckmaster, G.Joulin, & P.Ronney. "The structure and stability of nonadiabatic flame balls. II Effects of far-field losses", Combustion and Flame, vol.84, 411-422, 1991.

C.Brauner, J.Buckmaster, J.W.Dold, & C.Schmidt-Laine. "On an evolution equation arising in detonation theory", article in Fluid dynamical aspects of combustion theory, ed. M.Onofri, A.Tesei, Pitman Research Notes in Mathematics Series no.223, 196-210, 1991. The proceedings of a year long special program held at the Istituto per le Applicazioni del Calcolo 'Mauro Picone', Rome.

J.Buckmaster. "Mathematical topics in combustion", Chemometrics and Intelligent Laboratory Systems, vol.10, 189-198, 1991.

J.Buckmaster. " A flame-string model and its stability", Combustion Science and Technology, vol.84, 163-176, 1992.

J.Buckmaster. "Flame stability", article in Major Research Topics in Combustion, ed. M.Hussaini, A.Kumar, R.Voigt, ICASE/NASA LaRC Series, Springer-Verlag, 103-130, 1992.

J.Buckmaster & P.Clavin. "An acoustic-instability theory for particle-cloud flames", Proceedings of the 24th International Symposium on Combustion, 1992.

J.Buckmaster & C.J.Lee. "The effects of confinement and heat loss on outwardly propagating spherical flames", Proceedings of the 24th International Symposium on Combustion, 1992.

J.Buckmaster, R.Gessman, & P.Ronney. "The three-dimensional dynamics of flame-balls", Proceedings of the 24th International Symposium on Combustion, 1992.

J.Buckmaster, P.Ronney, & M.Smooke. 'Flame-balls - past, present and future", AIAA paper 93-0712, 1993.

J.Buckmaster. "The structure and stability of laminar flames", Annual Review of Fluid Mechanics, vol.25, 21-53, 1993.

J.Buckmaster & G.Joulin. "Influence of boundary-induced losses on the structure and dynamics of flame-balls", Combustion Science and Technology, vol.89, 57-69, 1993.

J.Buckmaster, M.Smooke, & V.Giovangigli. "Analytical and numerical modeling of flame-balls in hydrogen-air mixtures", Combustion and Flame, vol.94, 113-124, 1993.

Major Presentations during the Contract Period

July 1991. Workshop on combustion, Tsukuba, Japan (no cost).
July 1991. 13th International Conference on Dynamics of Explosives and Reacting Systems, Nagoya, Japan.
March 1992. Southwest Mechanics Lecture Series (no cost to contract).
July 1992. 3 papers at the 24th Symposium on Combustion, Sydney, Australia.
Fall 1992. Icase workshop on combustion (no cost).

Additional talks at workshops, universities, and APS meetings not listed.

Degrees Completed

Ph.D.	C.J.Lee, 1992.
M.S.	J.Hager, 1991.
	R.Gessman, 1992.
	A.Omar, 1992